Physics Based Modeling of Helicopter Brownout for Piloted Simulation Applications

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INTRODUCTION

The entrainment and circulation of ground dust and debris during rotorcraft take-off and landing over unprepared fields, often referred to as brownout, represents a serious operational problem for rotorcraft aviation. Recent experience in Afghanistan and Iraq has heightened the awareness of the impact of reduced visibility on safe rotorcraft operations in brownout conditions. Brownout related accidents have led to the loss of more than 20 helicopters and 50 lives since 2001 (Warwick, 2008). Improving safety during desert operations has received considerable attention in recent years, focusing on sensing and pilot cueing systems to augment situational awareness in the degraded visual environment associated with brownout (MacIssac et al., 2005; Walls et al., 2005), and more recently, a semi-automated system for hands-off landing in brownout conditions (Colucci, 2007).

Since helicopter pilots often first experience brownout in actual flight conditions, simulation and training in virtual environments can play an important role in preparing rotorcraft aviators for the potential hazards associated with brownout. Most current generation simulation environments, however, have rudimentary brownout visual simulations that are empirically driven. While these simulations provide a representative training environment, it is desirable to advance the state of training simulations by providing high fidelity modeling of brownout conditions during landing and take-off. Empirical and semi-empirical brownout visual models lack the level of fidelity required to capture the complex interaction of rotor downwash, ambient winds, and the effect of vehicle maneuvering, in combination with debris transport and visual obscuration effects due to the wide range of possible surface cover materials and ground topology. Thus, the focus of the present study has been to develop and implement physically-based models for brownout conditions in real-time simulations suitable for pilot training.

Modeling brownout conditions has received attention within the rotorcraft aeromechanics community, focusing on prediction of the rotorwash flow field using advanced modeling methods. For example, previous work used a time-averaged Navier-Stokes Computational Fluid Dynamics (CFD) analysis to effectively predict the rotor outwash for several rotorcraft configurations (Liu et al., 2001; Moulton et al. 2004). This analysis was subsequently used to generate the flow field in a recent CFD-based brownout analysis being developed by the U.S. Army (Ryerson et al. 2005). More recently, CFD flow solvers have been coupled with particle entrainment models to provide complete rotorcraft brownout and whiteout analyses (Haehnel et al., 2008, Phillips and Brown, 2008). These studies use methods that simulate the underlying physical processes through high-end computational analysis, but due to the computational requirements, do not offer a solution for real-time modeling and simulation applications.

In contrast to Navier-Stokes analyses, the brownout modeling methodology described in this paper is built upon potential flow methods that are well-suited for capturing vortex-dominated ground flows, which have been shown to be an important mechanism for rotorcraft dust entrainment (Keller et al., 2006). A primary component of the brownout methodology is the free wake analysis developed by Continuum Dynamics, Inc. (CDI) for comprehensive rotorcraft analysis and enhanced to support real-time simulation applications (Wachspress et al. 2003a, Wachspress 2008). This free wake analysis is referred to as the CHARM free wake model because it is found in CDI's Comprehensive Hierarchical Aeromechanics Rotorcraft Model (CHARM). This approach overcomes the primary shortcoming of CFD-based approaches, specifically real-time implementation, while providing a complete representation of the unsteady flow field surrounding a helicopter with fast turnaround during transient maneuvering flight. This

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capability is a critical requirement for brownout simulation and training applications.

This paper provides an overview of the real-time brownout methodology built upon free wake models for the rotorcraft flow field. A summary of the model architecture is given, with discussion of the primary components of the simulation model. Validation and verification of the brownout modeling approach is also summarized. The paper also summarizes work on the development and integration of a real-time module, which has been integrated into the U.S. Army Advanced Prototyping Engineering and Experimentation (APEX) laboratory at the System Simulation and Development Directorate on Redstone Arsenal in Huntsville, AL. Results from this joint integration effort are provided herein, where the brownout module was coupled with a rotorcraft flight simulation and image generator system for the UH-60M, CH-47F and ARH aircraft. An overview of the integration approach and representative results are provided.

ROTORCRAFT BROWNOUT SIMULATION MODEL OVERVIEW

An overview of the physically-based models used to construct the real-time rotorcraft brownout simulation is provided in this section. The key elements of the modeling approach, illustrated in Figure 1, are (1) a state-of-the-art rotorwash model using a real-time, free-vortex wake model and fast panel method to represent the complex flow field around a maneuvering rotorcraft in proximity to the ground; (2) a particle entrainment and transport model for determining the spatial distribution and concentration of debris due to low altitude rotorcraft operations; and (3) a visual obscuration model based on light scattering theory for determining the degraded visual scene within a simulation graphical database.

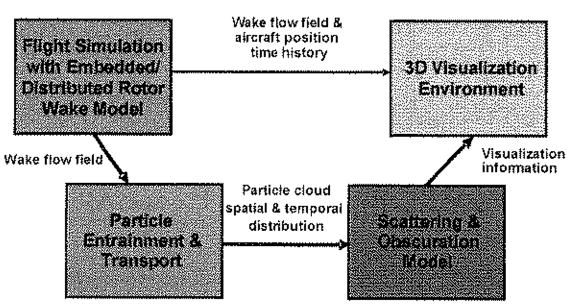

Figure 1. Block Diagram Illustration of Physics Based Rotorcraft Brownout Simulation

These modeling components are integrated into a runtime module that may be loosely coupled to a rotorcraft flight dynamic model and visualization environment (i.e., information transfer to and from the brownout module is one-way so that the brownout simulation can operate independently from the host simulation). Details describing the physical modeling basis are summarized below.

CHARM Rotorwash Model

The brownout wake model builds upon the methods used in the CDI CHARM rotorcraft analysis (Comprehensive Hierarchical Aeromechanics Rotorcraft Model). This model is a well-validated comprehensive rotorcraft analysis for modeling complete rotorcraft aerodynamics and dynamics in hover and forward flight (Wachspress et al., 2003a). CHARM couples a curved vortex element, full-span, free wake model with a vortex lattice lifting surface rotor blade model and a fast lifting surface source/doublet panel model of the airframe and ground. An option to model the ground as a vortex image plane is also available and was used for results in this paper. The model directly computes the roll-up of the vortex sheet trailed and shed from the full-span of each rotor blade into concentrated vortices, using a Constant Vorticity Contour (CVC) full-span free-vortex wake model. This approach predicts, rather than assigns, tip vortex roll-up characteristics, which is critical for general application to maneuvering flight simulations away from and near the ground. It is this ability that sets CHARM apart from similar analyses as a design tool for modeling transient flight where the vorticity in the wake continually change both spatially and temporally and thus cannot be assigned. Extensive validation work has shown the CHARM model to have unique capabilities in modeling the aeromechanics of rotor/wake/airframe configurations (Quackenbush et al., 1990; Wachspress et al., 2003a, 2003b).

The CHARM wake model has been modularized for direct coupling into flight simulations. In flight simulation applications, the CHARM wake typically evolves in the aircraft reference frame. Recent work has been performed providing an alternate solution method evolving the wake in the inertial reference frame. This capability was further enhanced to support brownout simulations, as well as other applications involving multiple aircraft simulations.

An additional capability incorporated in the CHARM wake model is the ability to include alternate wind gust and wake sources by means of a separate input module (subroutine). In practice, this additional wind gust

input can be the result of the wake from additional aircraft and/or ground structures, in addition to general atmospheric disturbances. This enhancement supports the goals of both real-time simulation and high fidelity assessment. For real-time applications, the subroutine may contain, for example, pre-computed look-up tables for complex induced velocity fields computed off-line prior to the calculation corresponding to buildings, aircraft operating in the vicinity, or variable wind conditions. The external wake input due to ambient wind or alternate wake sources is incorporated within the CHARM wake solution as a separate forcing term in the evolution of the wake structure, as opposed to simply superimposing the gust disturbance on the wake induced velocity. This approach provides an additional (nonlinear) interactional effect, yielding more accurate computational results.

Dust and Debris Transport Model

An equally critical feature of any brownout analysis is the prediction of ground debris entrainment and recirculation within the overall rotorwash flow field. The problem of sand/dust entrainment in wind has been studied for over 40 years in many applications including erosion modeling, sand dune formation and nuclear blast waves (Hartenbaum, 1971; Mirels, 1984; Denison and Hookham, 1995; Ryerson et al., 2005). Work focusing on the effects of rotorwash on debris entrainment and transport has examined scaling laws based on matching mathematical models with experiments (Kuhn, 1959; Rodgers, 1967; Tatom et al., 1967). While this prior work provides a broad basis for modeling dust and debris pick-up and transport, the present investigation has used an alternative approach.

For the real-time brownout model, debris transport is determined using analytical methods previously developed for modeling the surface pickup of chemical and biological agents by low flying helicopters. A central element of this work has been the development of the computer analysis LDTRAN (for Lagrangian Deposition and TRajectory ANalysis), which is part of a U.S. Army suite of analysis tools for simulating the effects of chemical/biological clouds on the passage of rotorcraft (Quackenbush et al., 1997). The LDTRAN methodology uses a Lagrangian trajectory analysis for tracking the trajectory of homogenous particle clusters. Trajectory equations in LDTRAN track the ensemble-averaged position of a group of similar sized particles subject to the aerodynamic shear (drag) and body (gravity) forces acting on the particles. In addition, the analysis also accounts for the growth in the standard deviation of material around the mean positions represented by an analytical solution of the turbulent fluid fluctuations in the atmosphere. Thus, the output defines the ensemble-averaged particle location and cloud standard deviation of a group of particles, which is ideally suited for the brownout problem. For relatively homogeneous ground cover, accurate solutions can be obtained while tracking only a small number of representative particle clusters, greatly reducing required CPU time and facilitating real-time operation. Furthermore, particle cluster standard deviations, provided directly from the LDTRAN analysis, provide inputs for determining visual obscuration (described in the following section), so that additional post-processing of the results is not required.

To initialize the dust/debris transport calculation, it is necessary to identify conditions under which surface debris is lifted from the ground. Dust or debris on the ground must first be moved laterally before being lifted vertically by the approaching aircraft wake. In the debris entrainment model, any material exactly on the surface will not be lifted by the helicopter wake since there is no vertical component to the relative flow velocity at the ground surface. The approach used for the real-time brownout model follows from a similar methodology used in atmospheric motion studies, when specifying wind speed, through the introduction of a surface roughness or canopy height. In this approach, it is assumed that the surface material begins at a characteristic displacement thickness above the ground, typically on the order of one foot. To be lifted by the approaching aircraft wake, the horizontal velocity at the displacement thickness height must be sufficient to overcome the sliding friction of the particle as it lies on the layers of dust or sand that comprise the canopy. Then, when in motion over the ground, the particle must move at a speed high enough so that gravity will not prevent it from lifting off the canopy. This criterion is summarized by the following relationship:

$$\frac{C_D \frac{1}{2}\rho_a U^2\left(\frac{\pi}{4}D^2\right)}{\mu\rho\left(\frac{\pi}{6}D^3\right)g} = \frac{C_D}{\mu}\frac{\rho_a}{\rho}\frac{U^2}{gD} > 1 \qquad \textbf{(1)}$$

where C_D is the particle drag coefficient, ρ_a is the air density, U is the local air velocity, D is the particle diameter, μ is a coefficient of static friction, and g is the acceleration due to gravity.

In Eq. (1), the local velocity U can be assigned either directly from the CHARM-predicted rotorwash field, or alternatively, by applying a logarithmic velocity

profile near the ground based on a reference velocity height, U_r, to model the viscous boundary layer, i.e.,

$$U = U_r \frac{\ln\left(\dfrac{z + z_o}{z_o}\right)}{\ln\left(\dfrac{z_r + z_o}{z_o}\right)} \tag{2}$$

where $U_r = U(z_r)$ with reference height z_r typically on the order of 2 meters. Note that more rigorous models of the saltation process by which sand/debris lifts off the ground in ambient winds can be implemented, although this approach has proven to be effective, in particular for low speed helicopter flight over thin layers of ground debris.

Visual Obscuration Model and Rendering

The final element of the real-time brownout model is to determine the visual obscuration effects based on the spatially- and time-varying distribution of dust/debris particles. Note that high-fidelity visual rendering of clouds, which accounts for realistic scattering and absorption effects based on physical principles, has been an area of significant research and development (Nishita et al., 1996; Harris and Lastra, 2001; Heinzlreiter et al., 2002; Harris et al., 2003; Schpok et al., 2003). A central element of some of these prior studies has been to leverage graphics processing unit (GPU) processing to include advanced physical and rendering effects, including multiple scattering paths and absorption effects. While these studies have led to very realistic rendering of clouds, a simplified approach has been implemented in the present application that derives from the underlying particle field representation in the LDTRAN model.

The visual obscuration model implemented in the real-time brownout simulation determines the opacity of the brownout cloud particle clusters, whose trajectories are determined from the rotorwash and particle transport analyses. The model accounts for the attenuation of incident light from single path extinction due to scattering and absorption effects (see Figure 2). The attenuation of the incident light can be determined by the following relationship:

$$I = I_o \exp\left\{-\int \gamma \, ds\right\} \tag{3}$$

where I_o is the incident light intensity (irradiance), I is the attenuated light intensity (radiance) due to extinction (scattering plus absorption) from the cloud, and γ is the extinction coefficient, which depends on the particle density distribution of the cloud:

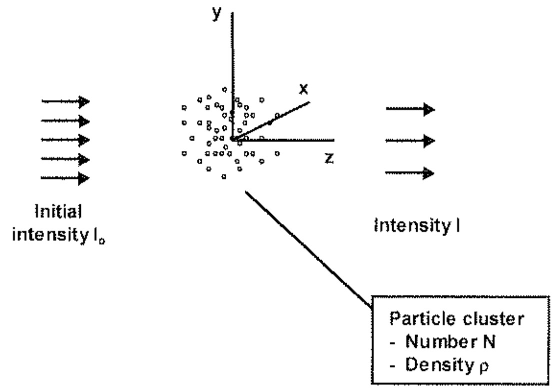

Figure 2. Parameter Definitions Used in Simplified Visual Obscuration Model

$$\gamma = \pi a^2 \rho Q \tag{4}$$

where a is the particle radius, ρ is the particle (number) density, and Q is the particle extinction efficiency factor. In general, this extinction factor varies with the scattering direction, and in general, is a complicated function of the particle size and optical properties, in addition to the spectral characteristics of the incident light (van de Hulst, 1981). For sufficiently large particles, the extinction efficiency may be approximated as a constant with value of 2.

To support real-time implementation, the attenuation of a particle cluster is determined analytically, where it is assumed that a single particle cluster represents a distribution of dust/debris particles with normal (Gaussian) spatial distribution:

$$\rho = \frac{N}{\sigma^3 (2\pi)^{3/2}} \exp\left(-\frac{r^2}{2\sigma^2}\right) \tag{5}$$

where N is the number of particles represented by the particle cluster, r is the distance from the particle cluster centroid, and σ is the particle cluster spread (which is calculated within the LDTRAN model). Note that Eqs. (3) through (5) can be solved analytically to yield the light attenuation function for a given particle cluster (see Keller et al., 2006 for additional details). For rendering the brownout cloud as individual particle clusters, the light attenuation

function can be used to control the relative transparency (i.e., alpha blending) of the cloud elements. This approach has formed the basis for visual rendering of the brownout cloud in a 3D immersive visualization environment, which has been implemented as a stand-alone visualization tool, in addition to the image generation system for a flight training application.

BROWNOUT MODEL VALIDATION AND VERIFICATION

This section outlines work toward validation and verification of the physical models that comprise the brownout simulation capability. Note that the CHARM and LDTRAN models have undergone extensive validation during their respective developments. Results are presented below that summarize validation of the real-time rotorwash model, which is the essential forcing function for brownout within a pilot-in-the-loop flight simulation. Results from qualitative verification of the model and plans for quantitative verification are also described.

Real Time Rotorwash Model Validation

Validation of the CHARM model in real-time rotorcraft flight simulation applications has been documented in Wachspress, 2008. Results presented here focus on validation of the real-time rotor outwash prediction capability which is the essential feature required for accurate physics-based brownout modeling in pilot-in-the-loop simulation.

An extensive validation of rotor outwash predictions using the real-time flow model was performed by correlating predictions with experimental and flight test data for CH-53 and XV-15 rotorcraft (Ferguson 1994). Representative results are shown in Figs. 3 and 4. Figure 3 shows mean and peak outwash at various heights above the ground one rotor diameter from the rotor center of a CH-53 Super Stallion helicopter hovering with its main rotor 37 ft above the ground. Fig. 4 shows similar correlations for an XV-15 tiltrotor. The predictions were made with a real-time wake model. A complete series of correlations like these was performed varying height and weight of the aircraft, and distance from the aircraft to establish the ability of the real-time wake model to predict not only the mean velocities but also the peak (fluctuating velocities) characteristic of helicopter rotorwash. Capturing mean and peak velocities is critical for properly predicting the entrainment and transport of the particles that constitute the brownout cloud.

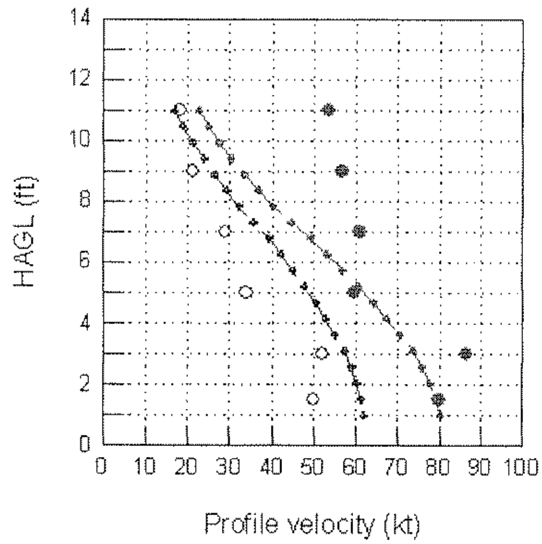

Figure 3. Mean (blue) and peak (red) outwash velocity near the ground one rotor diameter from the center of the rotor hub of a 70,000 lb CH-53 helicopter hovering with its main rotor 37 feet above the ground. Data are large circles, predictions are small circles connected by the dotted lines.

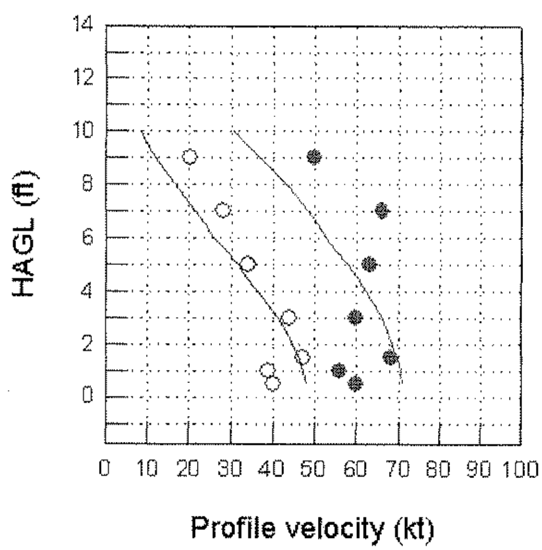

Figure 4. Mean (blue) and peak (red) outwash velocity near the ground one rotor diameter from the center of the left rotor hub of a 25,000 lb XV-15 tiltrotor hovering with its rotors 37 feet above the ground. Data are large circles, predictions are small circles lines.

Particle Transport Model Validation

The particle transport model used in the brownout model was extensively validated in prior work where correlations were performed with over 1500 deposition data points obtained from a series of 180 field trials (Bird et al., 2002). Figure 5 shows a comparison of measured and predicted deposition from these studies.

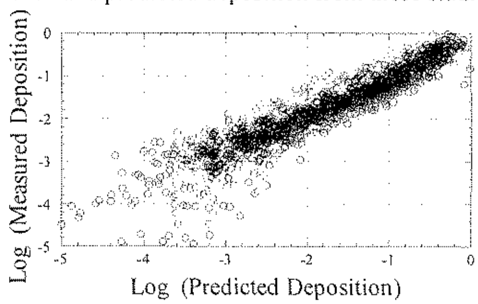

Figure 5. Measured and predicted deposition for a series of 180 field trials, (Bird et al. 2002).

Qualitative Verification of Brownout Model

Once the brownout model was integrated into the U.S. Army flight simulation, qualitative validation was performed by a pilot who has experienced brownout in the field. The pilot recorded that the cloud appeared qualitatively at the correct heights and speeds.

Anecdotal evidence indicates that brownout may be strongly influenced by details of the rotorcraft aerodynamics and flow field that may not be easily captured by simplified semi-empirical models used in current generation flight simulation environments. For example, differences in the brownout characteristics of similar aircraft have been noted. It is highly desirable to be able to capture large scale changes in the brownout cloud characteristics as a function of aircraft platform and operational characteristics.

Fig. 6 illustrates a qualitative verification of aircraft-to-aircraft brownout cloud differences. In this example, two different helicopters are flown through the identical landing flare trajectories, and the resulting brownout clouds as determined by the model are captured. Note that for the two helicopters shown, the gross weight differs by approximately 50 percent, although the average rotor downwash in hover are more closely matched (average downwash differ by approximately 10 to 15 percent). Although the average downwash (and hence rotor outwash) are similar for these helicopters, a very significant difference in the resulting brownout clouds can be observed. A similar difference has been reported by pilots operating these aircraft in the field. This qualitative verification of the model underscores the importance of high-fidelity physical representations of the brownout simulation, especially if simulation will be used to train pilots for operations in brownout conditions prior to deployment in the field.

Quantitative Verification of Brownout Model

The difficulty in acquiring representative experimental data that define dust/debris particle deposition and/or quantifying visual obscuration inhibits formal validation of the complete analysis. However, ongoing correlations are being performed with brownout field data that is available in the literature, (Rodgers 1968, Cowherd 2007).

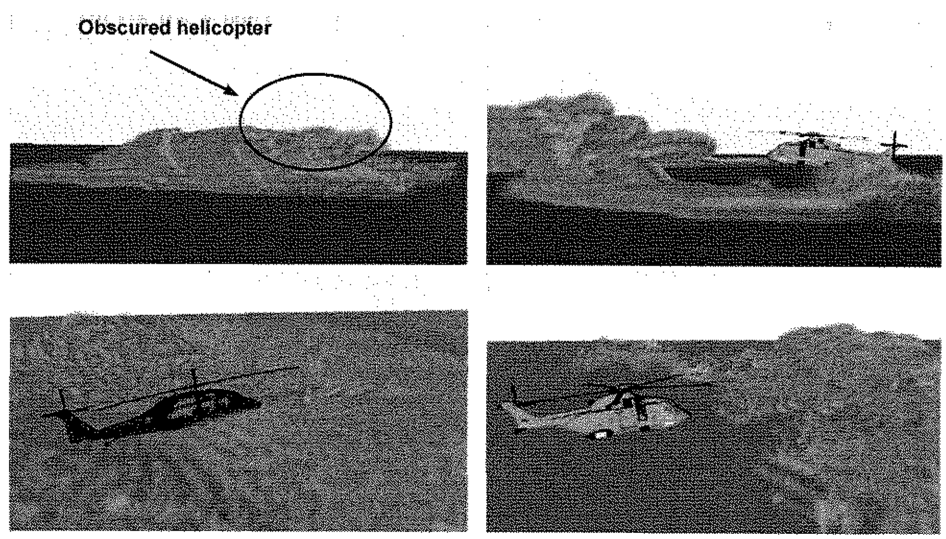

Figure 6. Comparison of Brownout Cloud for Two Different Helicopters Following Identical Trajectories

BROWNOUT MODULE INTEGRATION

The physical models comprising the brownout simulation have been incorporated into a stand-alone analysis tool, as well as a real-time module for application to piloted simulation. Work has been performed to integrate and demonstrate this real-time, physics-based brownout module in the U.S. Army Advanced Prototyping Engineering and Experimentation (APEX) laboratory. An overview of this simulation integration and results from initial demonstrations are presented below.

APEX Laboratory Simulation Integration

The real-time brownout module, built upon the physical models described previously, has been integrated into the APEX laboratory rotorcraft flight simulation for the UH-60M, CH-47F and ARH aircraft and image generator system at the System Simulation and Development Directorate on Redstone Arsenal in Huntsville, AL. The simulation architecture used for demonstration was the APEX laboratory Battlefield Highly Immersive Virtual Environment (BHIVE). The BHIVE simulation consists of six high fidelity projectors that display a virtual scene onto a dome screen allowing a 180 degree by 75 degree field of view. An illustration of the brownout module integration within this architecture is shown in Fig. 7.

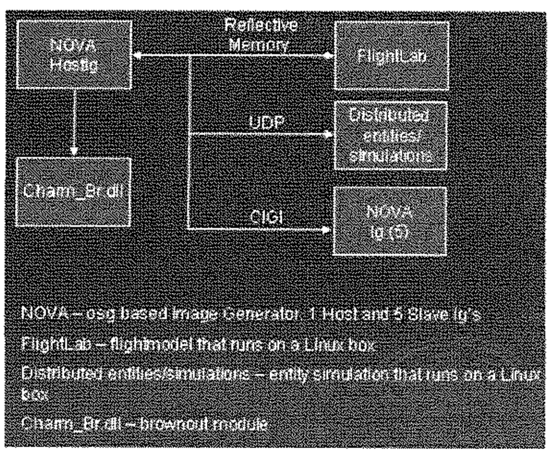

Figure 7. Illustration of the Brownout Module Integration within the APEX Laboratory BHIVE Simulation.

The image generation software, called NOVA, is built upon the Open Scene Graph (OSG) technology and for the BHIVE consists of one Host image generator (IG) and 5 Slave IGs which are synched together using CIGI messages. The Host IG uses reflective memory technology to communicate with the flight dynamics models and then sends updates to the Slave IGs through a UDP socket.

The run time process with the brownout model involves begins with a one time call to initialize the brownout model with the characteristics of the helicopter (e.g. rotor rotation rate, thrust coefficient, position and orientation in the aircraft frame, etc.) The next step is to make a per frame call at a 60 hertz rate to send updated aircraft states to the brownout module. The last step is to make a per frame call to retrieve updated information for each dust particle cluster. The dust particle clusters are represented graphically using OSG billboards and an OpenGL shader. The shader is controlled by three attributes (sigma, alpha, and particle size). The Host IG queries the terrain for a height above terrain (HAT) that is then sent to the brownout module.

In the simulation implementation, algorithms have been incorporated into the brownout model that allow it to remove ground and airborne particle clusters from behind the aircraft and insert ground particle clusters in front of the aircraft. This retains only the portion of the cloud visible from the cockpit. This feature significantly improves the cloud resolution possible in real-time applications.

The brownout module has been successfully integrated and demonstrated within the APEX BHIVE simulation. Representative screen shots from the simulation are shown in Figures 8 through 10, illustrating a simulated brownout cloud generated for an ARH helicopter.

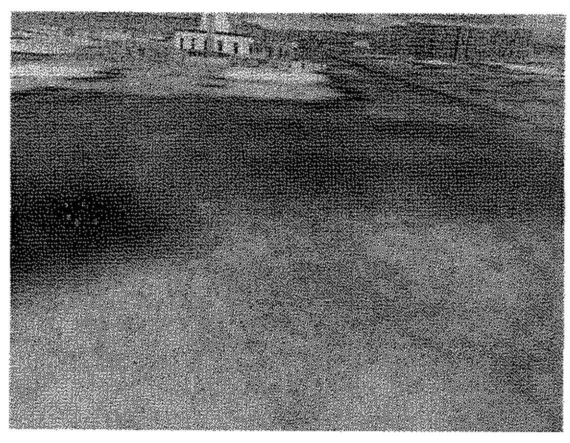

Figure 8. Screenshot for APEX BHIVE Brownout Simulation Illustrating Onset of Brownout Conditions

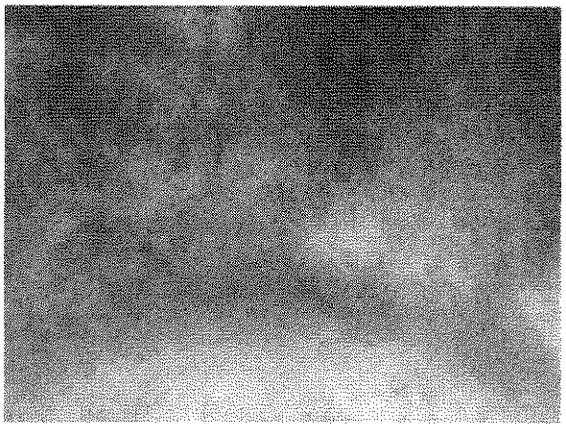

Figure 9. Screenshot for APEX BHIVE Brownout Simulation Illustrating Immersion in Brownout Cloud.

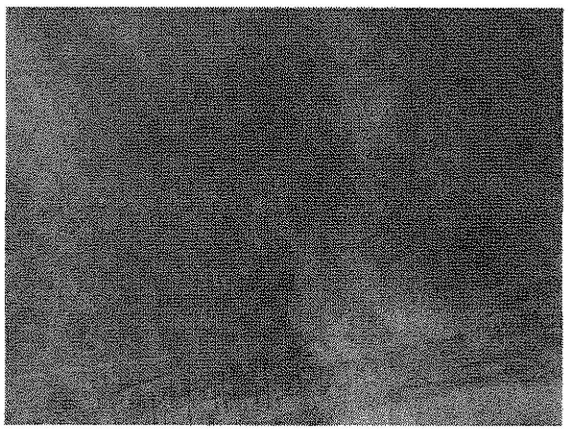

Figure 10. Screenshot for APEX BHIVE Brownout Simulation During Brownout Moderate Conditions.

CONCLUDING REMARKS

Entrainment of dust and debris by rotorwash during the take-off and landing of rotorcraft can result in a dangerous brownout condition characterized by severely limited visibility and damage to engine parts and rotor blades. This paper describes the development and application of a physics-based, brownout module for flight simulations able to characterize and render brownout conditions for general rotary-wing aircraft, wind, ground topology and flight maneuvers in real-time. The key advantage of the physics-based model over current models is that the simulator pilot experiences the actual brownout conditions specific to the aircraft, flight condition and ground cover instead of merely having the cockpit view "brownout" when flying low and slow. While it is important to practice zero visibility landings, the new brownout module allows pilots to also learn which flight maneuvers lead to brownout and which avoid brownout for a specific aircraft.

A key enabling technology for the new brownout module is the CHARM real-time free-vortex wake model which has the unique ability to predict the rotor wake flow field in the vicinity of the aircraft and ground at the required fidelity in a real-time simulation environment. This capability was validated through extensive correlation with rotor outwash flight test data. A second key enabling technology is the LDTRAN particle transport model. This was validated through correlation of ground deposition predictions from an extensive series of field studies involving various aircraft performing fly-bys.

The brownout module was successfully integrated into the U.S. Army Advanced Prototyping Engineering and Experimentation (APEX) laboratory rotorcraft flight simulation for the UH-60M, CH-47F and ARH aircraft. Qualitative validation of the complete brownout module was performed by pilot evaluation in the APEX flight simulation. Future work will include quantitative validation of the complete brownout model through correlation with field test data and increasing the frame rate throughput of the model in the flight simulation through hardware and configuration modifications. Future work will also include the ability to feed ground cover information to the model directly from the terrain database. In the current model, brownout can either occur everywhere near the ground or at a specified landing site, and the ground cover characteristics are set by user input to the brownout module at initialization rather than interrogation of the terrain database.

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REFERENCES

Bird, S.L., Perry, S.G., Ray, S.L. and Teske, M.E. (2002). "Evaluation of the AgDISP Aerial Spray Algorithms in the AgDRIFT Model," Environmental Toxicology and Chemistry, Vol. 21 No. 3, pp.672-681, 2002.

Colucci, F. (2007). "'Sandblaster' Gives Helicopter Pilots Hope for Safer Landing." *National Defense*, from http://www.nationaldefensemagazine.org, August 2007.

Cowherd, C. (2007), "Sandblaster 2 Support of See-Through Technologies for Particulate Brownout," Task 5 Final Technical Report, U.S. Army Aviation Missile Command Contract No. W31P4Q-07-C-0125, October 2007.

Denison, M.R. and Hookham, P.A. (1995). "Modeling of Dust Entrainment by High-Speed Air Flow." 26th AIAA Fluid Dynamics Conference, San Diego, CA, June 1995.

Ferguson, S.W. (1994). "Rotorwash Analysis Handbook Volume I – Development and Analysis." DOT/FAA/RD-93/21, June 1994.

Haehnel, R.B., Moulton, M.A., Wenren, Y., and Steinhoff, J. (2008). "A Model to Simulate Rotorcraft Induced Brownout." American Helicopter Society 64th Annual Forum, Montreal, Canada, April 2008.

Harris, M.J. and Lastra, A. (2001). "Real-time Cloud Rendering." *Eurographics 2001*, Vol. 20, (3).

Harris, M.J., Baxter, W.V., Scheuermann, T., and Lastra, A. (2003). "Simulation of Cloud Dynamics on Graphics Hardware." Graphics Hardware 2003.

Hartenbaum, B. (1971). "Lofting of Particulates by a High-speed Wind." Defense Nuclear Agency, DNA-2737, September 1971.

Heinzlreiter, P., Kurka, G., and Volkert, J. (2002). "Real-Time Visualization of Clouds." 10th International Conference in Central Europe on Computer Graphics, Visualization and Computer Vision, February 2002.

Keller, J.D., Whitehouse, G.R., Wachspress, D.A., Teske, M.E., and Quackenbush, T.R. (2006). "A Physics Based Model of Rotorcraft Brownout for Flight Simulation Applications." American Helicopter Society 62nd Annual Forum, Phoenix, AZ, May 2006.

Kuhn, R.E. (1959). "An Investigation to Determine Conditions Under Which Downwash from VTOL Aircraft Will Start Surface Erosion from Various Types of Terrain." NASA TN D-56, September 1959.

Liu, J., McVeigh, M.A., and Rajagopalan, G., "Single- and Dual-Rotor Flowfield and Outwash Predictions," American Helicopter Society Tiltrotor/Runway Independent Aircraft Technology and Applications Specialists' Meeting, Arlington, TX, March 2001.

MacIsaac, M., Stiles, L., and Judge, J. (2005). "Flight Symbology to Aid in Approach and Landing in Degraded Visual Environment." American Helicopter Society 61st Annual Forum, Grapevine, TX, June 2005.

Mirels, H. (1984). "Blowing Model for Turbulent Boundary-Layer Dust Ingestion." *AIAA Journal*, Vol. 22, (11), November 1984.

Moulton, M.A., O'Malley, J.A., and Rajagopalan, G., "Rotorwash Prediction Using an Applied Computational Fluid Dynamics Tool," American Helicopter Society 60th Annual Forum, Baltimore, MD, June 2004.

Nishita, T., Dobashi, Y., and Nakamae, E. (1996). "Display of Clouds Taking into Account Multiple Anisotropic Scattering and Sky Light." *ACM SIGGRAPH*.

Phillips, C. and Brown, R. (2008). "Eulerian Simulation of the Fluid Dynamics of Helicopter Brownout," American Helicopter Society 64th Annual Forum, Montreal, Canada, April-May 2008.

Quackenbush, T.R., Bliss, D.B., Wachspress, D.A., Boschitsch, A.H., et al. (1990). "Computation of Rotor Aerodynamic Loads in Forward Flight Using a Full-Span Free Wake Analysis." NASA CR 177611, October 1990.

Quackenbush, T.R., McKillip, R.M., Curbishley, T.B., and MacNichol, A.Z. (1997). "LDTRAN/CB: A Model for the Assessment of the Impact of the Chemical/Biological Environment on Military Rotorcraft Operations." American Helicopter Society 53rd Annual Forum, Virginia Beach, Virginia, April 1997.

Rodgers, S.J. (1967). "Evaluation of the Dust Cloud Generated by Helicopter Rotor Blade Downwash." 7th Annual Conference on Environmental Effects on Aircraft and Propulsion Systems, Princeton, NJ, September 1967.

Ryerson, C.C., Haehnel, R.B., Koenig, G.G., and Moulton, M.A., "Visibility Enhancement in Rotorwash Clouds," 43rd AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, January 2005.

Schpok, J., Simons, J., Ebert, D.S., and Hansen, C. (2003). "A Real-Time Cloud Modeling, Rendering, and Animation System." Eurographics/SIGGRAPH Symposium on Computer Animation.

Tatom, J.W., Hinson, B.L., and Harris, A.E. (1967). "VTOL Transport Dust Cloud/Pilot Visibility Model Study." 7th Annual Conference on Environmental Effects on Aircraft and Propulsion Systems, Princeton, NJ, September 1967.

van de Hulst, H.C. (1981). *Light Scattering by Small Particles*, Dover Publications, New York, NY.

Wachspress, D.A., Quackenbush, T.R., and Boschitsch, A.H. (2003a). "First-Principles, Free-Vortex Wake Model for Helicopters and Tiltrotors." American Helicopter Society 59th Annual Forum, Phoenix, AZ, May 2003.

Wachspress, D.A., Quackenbush, T.R., and Boschitsch, A.H. (2003b). "Rotorcraft Interactional Aerodynamics with Fast Vortex/Fast Panel Methods." *Journal of the American Helicopter Society*, Vol. 48, (4), October 2003.

Wachspress, D.A., Keller, J.D., Quackenbush, T.R., Whitehouse, G.R., and Yu, K. (2008). "High Fidelity Rotor Aerodynamic Module for Real Time Rotorcraft Flight Simulation." American Helicopter Society 64th Annual Forum, Montreal, Canada, April 2008.

Walls, C.S., Paris, S.M., Wood, J.A., and Scoggin, N. (2005). "Brownout Situational Awareness Upgrade (BSAU) Development and Integration on the CH-47D and UH-60L Helicopters." American Helicopter Society 61st Annual Forum, Grapevine, TX, June 2005.

Warwick, G. (2008). "High Level Pentagon Project Pursues Brownout Solutions." Aviation Week and Space Technology, 5 May 2008, p. 34.